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New Digital Control and Power Protection System of VR-1 Training Reactor

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ABSTRACT

The contribution describes the new VR-1 training reactor control and power protection system at the Czech Technical University in Prague. The control system provides safety and control functions, calculates average values of the important variables and sends data and system status to the human-machine interface. The upgraded control system is based on a high quality industrial PC. The operating system of the PC is the Microsoft Windows XP with the real time support RTX of the VentureCom Company. The software was developed according to requirements in MS Visual C. The independent power protection system is a component of the reactor safety (protection) system with high quality and reliability requirements. The digital system is redundant; each channel evaluates the reactor power and the velocity of power changes and provides safety functions. The digital part of the channel is multiprocessor-based. The software was developed with respect to nuclear standards. The software design was coded in the C language regarding the NRC restrictions. Configuration management, verification and validation accompanied the software development. Both systems were thoroughly tested. Firstly, the non active tests were carried out. During these tests, the active core of the reactor was subcritical; the input signals were generated from HPIB and VXI controlled instruments to simulate different operational and safety events. The software for instruments control and tests evaluation utilized Agilent VEE development system. After the successful non active checking, the active tests followed.

1 INTRODUCTION

The contribution deals with the new VR-1 training reactor control and power protection systems. The installation of both systems is an integral part of the VR-1 reactor I&C upgrade carrying out at the Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague. The general supplier of the systems was the Škoda Plzeň Company with an extensive cooperation of the Department.

The VR-1 training reactor has been operated since 1990 by the Department of Nuclear Reactors of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. The reactor was designed and constructed by the Škoda Company in co-operation with the Faculty.

The VR-1 reactor is a pool-type light-water reactor based on enriched uranium (36%). Its thermal power is rated up to 5kW. The moderator of neutrons is light demineralised water that is also used as a reflector, a biological shielding, and a coolant. The reactor is utilized primarily for training university students and nuclear power plant staff. The training on the VR-1 reactor is oriented to the reactor and neutron physics, dosimetry, nuclear safety, and control of nuclear installations. Students not only from technical universities, but also from universities of natural science are coming to the reactor for training. Scientific research has to respect reactor parameters and requirements of the so-called clean reactor core (free from a major effect of the fission products). Research on the VR-1 reactor is mainly aimed at the preparation and testing of new training methods, investigation of reactor lattice parameters, study of reactor dynamics, research in the field of control equipment, neutron detector calibration, etc.

The VR-1 training reactor has been operated since 1990 by the Department of Nuclear Reactors, at the Faculty of Nuclear Sciences and Physical Engineering of The Czech Technical University in Prague. The reactor was designed and built by the Škoda Company in co-operation with the Faculty. The reactor control and safety system (I&C) was developed in the mid- 80s. Even though the present control and safety system fully covers the demands that are put on it, its technical design is obsolete to a certain extent at the present time. There are also problems with maintenance because of a lack of spare parts. Furthermore, during its development and production, some new internationally respected demands to ensure the quality and the qualification (e.g. the IAEA, IEC, and IEEE recommendations and standards) were not or could not be considered. Therefore, it was decided to upgrade the present control and safety system with the aim to apply the latest available techniques and technology observing the above-mentioned recommendations and standards.

The principal upgrade of the control and safety system was started during the year 2001. Because of the frequent utilization of the VR-1 training reactor during the academic terms, it was decided to carry out the upgrade of the control and safety system gradually – in stages during holidays so as not to affect the training at the reactor. The first stage was the human-machine interface and the control room upgrade in 2001 [1]. During the second stage of the upgrade in 2002, the control rod drives and the safety circuits were replaced [2]. The third stage – the control system upgrade – was carried out in 2003. The next upgrade stage is the independent power protection upgrade. The new independent power protection channel was developed in 2004; channel tests and installation are under way now (summer 2005). After a successful licensing process at the Czech State Office for Nuclear Safety, the new channels are going to be installed into the reactor control and safety system during the summer holiday 2005. The last stage will be the operational power measuring channels upgrade, probably in 2006 or 2007.

2 CONTROL SYSTEM UPGRADE

The VR-1 training reactor control system upgrade as the third stage of the whole I&C upgrade was accomplished in the summer 2003.

2.1 Control System Structure

The control system utilizes an industrial PC and Simatic S7-200 PLCs for some distributed functions. The operating system of the PC is Microsoft Windows XP with the real time support RTX of the VentureCom Company. The block diagram of the new control system and its incorporation into the reactor I&C is shown in Figure 1.

The upgraded control system is based on a high quality industrial PC mounted in a 19" crate. The control computer receives data from the operational power measurement (OPM) channels in the full power range and the independent power protection (IPP) channels in the two highest power decades range via serial lines. The control computer checks received data from the OPM and IPP channels mutually and against the safety limits. If either the safety limits or allowed deviations between individual channels are exceeded or if there are any problems in the system, the safety action is initiated by the control computer.

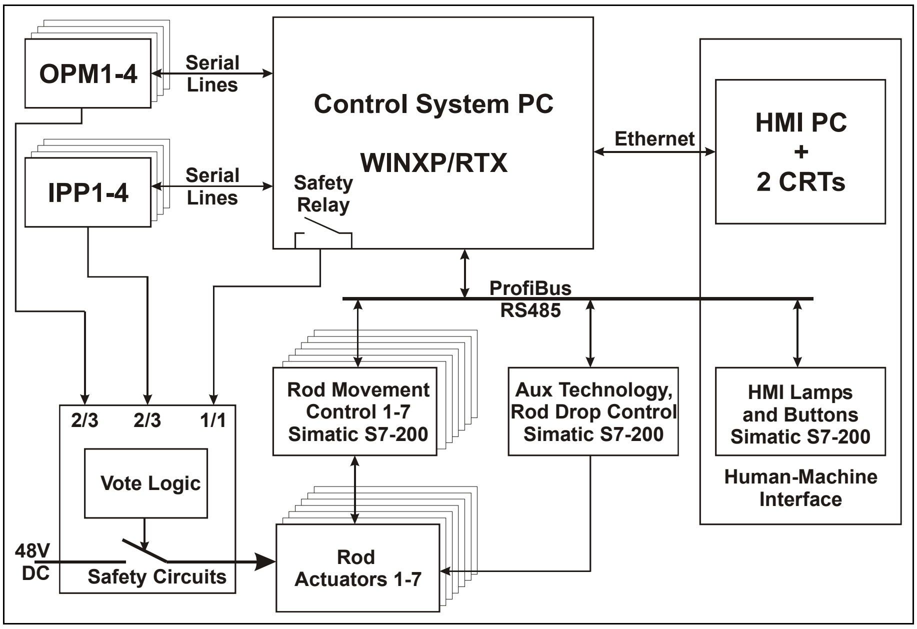

Figure 1: Control system block diagram

Next, the control system controls the reactor operation and provides the I&C diagnostics. It also serves as an automatic power control system; it controls the movement of the reactor control rods to obtain the required reactor power.

The control computer drives the absorbent rod movement via the rod actuators based on the Simatic S7-200 PLCs and connected with the control computer via ProfiBus (RS485) interface. The ProfiBus, together with the adjacent Simatic PLC is also utilized for auxiliary technology and individual rod drop control, then one also for lamps control and buttons scan on the operator's desk of the human-machine interface.

The control computer sends data via the Ethernet network to a human-machine interface computer and receives commands from there. If the commands are permitted, it carries them out.

2.2 Control System Software

The control system software represents a complex product. The software, together with the whole control system, is categorized according to the importance to nuclear safety as safety related. The quality assurance process, covering the whole software life cycle and including software requirements, design, coding, HW/SW integration and installation, was carried out. The documents 'Quality assurance plan', 'Verification and validation plan' and 'Configuration management plan' were prepared. Software development was accompanied with thorough testing, and the integrated system was carefully validated by simulated input signals and then in normal reactor operation.

2.2.1 Software Requirements

The software requirements were prepared as a text document [3]. The extent of the software requirements is of 170 pages. The requirements define the reactor operational modes and submodes. The requirements for cooperation with other reactor I&C (OPM, IPP channels, human-machine interface) were also formulated.

2.2.2 Control System Software Description

The control system software was prepared according to the requirements in the Microsoft Visual C++ development tool with RTX support. The software for single Simatic PLCs was established by proper Siemens development tools. The control system software consists of safety, control and diagnostics functions.

Firstly, the safety functions are described. The control system is equipped with a safety relay. If the safety action (reactor scram) is required, then the safety relay is switched off. The safety relay output is connected to the vote logic of safety circuits, and this signal is evaluated in the logic 1 out of 1. This means that if the control system safety relay is switched off, then the reactor is scrammed. The control system receives data from the OPM and IPP channels, compares power and velocity values with safety limits, it also compares data from individual channels and if the safety limits are exceeded, then initiates the safety action. It calculates the average values of power and velocity and evaluates the deviation between the real power and the demanded power value set by the operator. If the deviation limit is exceeded, the safety action is also initiated. The control system also checks the technology (e.g. control rod drives, PLCs), and if any problem occurs, it initiates the reactor scram.

Next, the control functions drive reactor modes, submodes and transition among them. The control system also receives commands and button signals from the human-machine interface, and if the action is in current operational mode and submode permitted, then appropriate response is executed. The software also calculates average values of the reactor power and velocity of power changes and sends them to the human-machine interface. The control system also provides the function of the automatic power regulator. The regulator compares the given power with the real reactor power and according to the deviation, it controls the rod movement.

Finely, the control system provides also diagnostic functions. It can check proper operation of the OPM and IPP channels and correct communication with other parts of the reactor I&C. The absorbent rod test was added to the original control system. This test can check the movement speed and the drop time of any rod. This is important for rod verification and maintenance.

2.3 Control System Tests

The control system was firstly tested with simulated signals and subcritical active core of the reactor to check its correct safety and control function. After the successful simulation tests, the reactor and the I&C were put into normal operation, and again the safety and control functions were checked. Secondly, after the successful simulation test, the equipment was tested during the reactor operation with enhanced safety measures.

2.3.1 Control System Tests with Simulated Signals

To test the control system with simulated signals, it was necessary to provide 4 independent pulse signals and 4 independent current signals for the OPM channels (the IPP channels operated within these tests with a standard neutron chamber signal). All available equipment was collected to assure enough simulated signals.

A block diagram of the control system testing is shown in Figure 2. The pulse generators are HPE1441E in the VXI rack, controlled via the FireWire; then HP33120A, HP8110A and HP81101A controlled via the HPIB. The current signal is produced in the universal source HP3245A (two current channels) and in two DC power supplies HPE3631A with simple electronics for voltage/current conversion, controlled via the HPIB. The complete testing system is controlled by a program designed in HP VEE. The program can generate different courses on individual signal outputs.

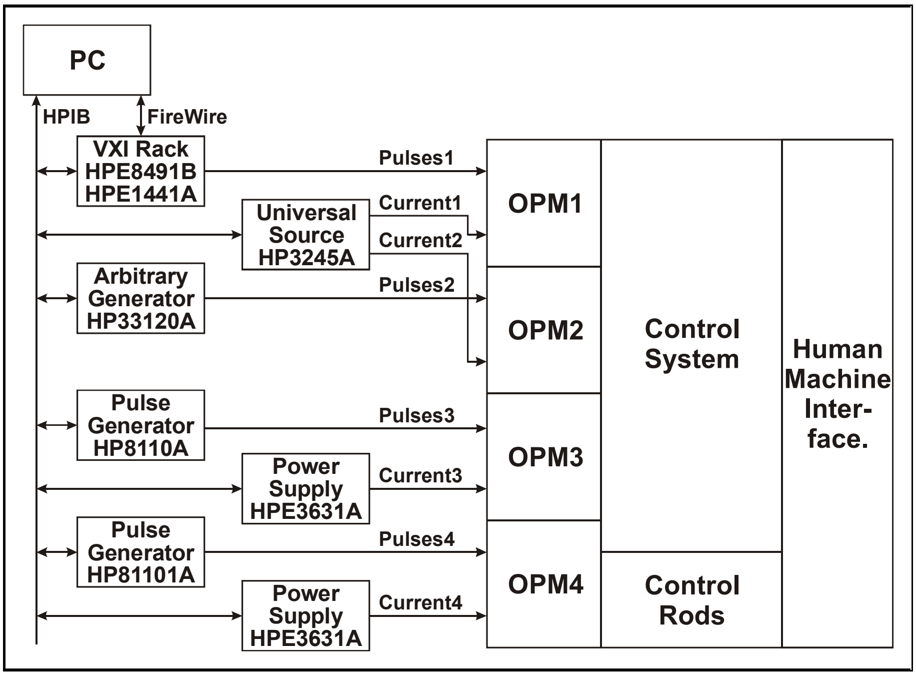

Figure 2: Block diagram of control system testing

All modes, submodes and transition among them, rod movement and safety features together with proper safety circuits functionality (1 out of 1 logic) were tested. Also the evaluation of data from the OPM channels, calculations of average values and checks of deviation among individual channels were verified.

2.3.2 Control System Operational Tests

During the control system operational tests, the reactor active core was put into a standard configuration. Again, all safety features of the control system and transitions among reactor modes and submodes were tested. All control functions, commands and validity of their execution were verified. Finally, an automatic power regulator was tested.

3 INDEPENDENT POWER PROTECTION SYSTEM UPGRADE

The development of the new independent power protection (IPP) channel started in 2004. The general contractor of the project is Škoda Nuclear Machinery Company Plzeň, the hardware and software subcontractor is Tedia Limited. The Department of Nuclear Reactor prepared general, hardware and software requirements [4], software quality assurance, verification & validation and configuration management plans [5], developed the safety software for calculating units (see later) and carried out validation. The Department took an active part in the site acceptance tests of the system.

Following chapters describe the IPP channel hardware, software and verification & validation.

3.1 IPP Channel Hardware

The IPP channel hardware consists of an analog and a digital part. The analog part processes the signal from the boron neutron chamber, amplifies it and provides proper discrimination of neutrons.

The digital part counts pulses from the neutron chamber, evaluates the reactor power and velocity of power changes. Next, it checks gained data with the safety limits and sends the safety signal (controls the safety relay). It also communicates with the reactor control system via fiber optics lines, controls the individual display on the operator's desk and provides testing of the channel.

The IPP channel hardware was developed according to the IPP channel Hardware Requirements [8]

3.1.1 Analog Part of IPP Channel

The IPP channel sensor is the neutron boron chamber SNM-12 from Russia. The power supply for the chamber provides a high voltage power supply. The high voltage power supply is controlled by the digital part to provide chamber characteristic measurements. The signal from the chamber is amplified by an amplifier and evaluated by a discriminator. The discriminator level is set by the D/A from the digital part Auxiliary Unit (see later). The variable setting of the discrimination level can be used for chamber characteristic measurement and low discrimination tests during the reactor start-up.

The signal from the chamber can be replaced by a test signal to provide tests of the channel. The test signal of proper frequency is connected to the amplifier and a corresponding response of the channel is checked.

The pulses from the discriminator are connected to the counter of the IPP channel digital part that counts number of pulses in 0.1 second. The digital part computer units then read the frequency of neutron pulses (during standard operation proportional to the reactor power).

3.1.2 Digital Part of IPP Channel

A block scheme of the digital part of the IPP channel is shown in Figure 3. The digital part consists of 5 microcomputer units. The reason for the utilization of more microcomputers was to divide single functions to separate microcomputers to guarantee easier structure of the system hardware and in particular of system software. The communication among individual microcomputers is provided via buffer (bidirectional RAM) in a FPGA (Field-Programmable Gate Array). The used microcomputers are 8051 compatible, which are manufactured by the Silicon Laboratories Company. They are equipped with enough Flash EPROM and RAM; the FPGA was manufactured by the Altera Company.

In the following chapters, the single components of the IPP channel digital part are delineated.

The 16 bit Counter counts number of neutron pulses from the analog part. The interval of the counter is 0.1 second. The Calculating Units (see later) can read data from the counter. The counter overflow can be checked. The counter is implemented in the FPGA.

The Calculating Units 1 and 2 read data (count of neutron pulses) from the Counter, calculate reactor power and velocity of power changes. Furthermore, they check safety limits and send safety signal to the Safety Relay Control if the safety limits are exceeded. The units write calculated data to the Buffer.

There are two units in the channel. They work parallel and synchronized, and a Supervisory Unit examines if both units gives the same results. This feature provides protection against the unit memory or microcomputer failure because these units are together with the Safety Relay Control and the Safety Relay the most important for nuclear safety.

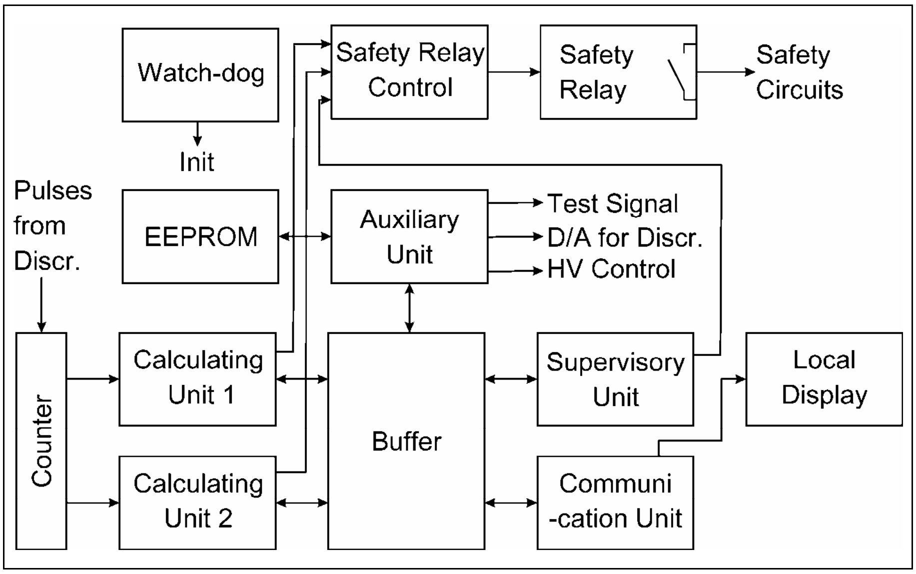

Figure 3: Structure of the digital part of the IPP channel

The Supervisory Unit reads data from Calculating Unit 1 and 2, checks that the data appear on time, compares them, and if a difference appears, it sends the safety signal to the Safety Relay Control that switches the Safety Relay off.

The Buffer is responsible for communication among the individual microcomputer units in the channel. The Buffer contains bidirectional RAM. There is the address space reserved for each unit there.

The Safety Relay Control is implemented in a CPLD (Complex Programmable Logic Device). This CPLD receives signals from the Calculating Units 1, 2 and the Supervisory Unit. If all of the three previously mentioned components work properly, and no safety problem appears, they send pulses every 0.1 second, and the Safety Relay is switched on. If any problem in one of the components arises (logic 1 out of 3), the pulses are not sent, and the Safety Relay is switched off. The status of the Safety Relays from all IPP channels is evaluated in the vote logic of the reactor safety circuits (see 2.2).

A high quality Safety Relay with forcibly guided contacts was utilized in the IPP channel to guarantee high reliability and safety.

The Communication Unit is responsible for communication among the IPP channel, the Control System, the Local Display and individual display. It reads data from the Buffer and sends them to the proper communication line. The unit reads also messages from the Control System line and writes them into the Buffer.

The communication unit provides also service line for calibration and maintenance of the IPP channel.

The Auxiliary Unit initiates the FPGA after the switch on of the channel, reads calibration data from the EEPROM, sets D/A converter for the discrimination level, provides the analog part test signals and controls the high voltage power supply.

The Watch-dog receives periodically signals from the system, and if one of the signals does not appear on time, it resets (initiates) the whole channel. After the reset, the channel is set in the operational regime 'reserve' and its Safety Relay is switched off. To change the regime to the 'measurement' status, it is necessary to receive corresponding command from the Control System.

The Local Display is situated on the front panel of the IPP channel and represents data and operational status of the channel.

3.2 IPP Channel Software

The software of the IPP channel was developed according to the Software requirements [4]. The IPP channels are components of the reactor protection system. There are strong requirements for their quality, reliability and availability. To achieve these goals, the appropriate standards were applied [6], [7].

The functional division of the IPP channel into the single microcomputers facilitates the software development because the software is then considerably less complex. Also, it is not necessary to utilize interrupts in the software of the Calculating Units, which is the most critical for the safety.

The IPP channel software life cycle was in compliance with the IEC-880 standard [6]. Firstly, the principal documents for the software development were established – the Quality Assurance, Verification & Validation and Configuration Management Plans [5]. These documents define basic procedures and techniques during the development and testing of the software. The whole life cycle was accompanied by the verification & validation.

The software life cycle started with formulation of requirements, continued with the software design, coding and integration of hardware/software. The whole life cycle was accompanied by the verification & validation. During the whole life cycle, the relevant documents according to [5] were prepared.

The Software Requirements were prepared as a standard text. The experience with formulation of Control System software requirements from the previous stage of the Control and Safety System upgrade was utilized. The principle requirements for safety functions of the IPP channel were prepared with attention. The warning and safety limits for the reactor power and velocity of power changes were set; the unacceptable channel states were defined. Reactor physicists and operation experts were involved in the preparation of the Software Requirements.

The software was then designed according to the Software Requirements. The software structure for the single units and the way of communication among them were established. The software was designed in the top-down manner. The basic algorithms and data structures were proposed, the algorithms (e.g. for the reactor power and velocity of power changes) were thoroughly tested.

The main programming language for the software coding was the ANSI C language with restrictions according to the standard [7]. Some parts of software were coded in the Assembly language (typically the parts with directly linked with the hardware), but the utilization of the Assembler was competently justified. The software was coded in the bottom-top manner. For the software coding and production, the reputable µVision 2 development system for 8051 compatible microcomputers of the Keil Software Company was utilized.

During the integration hardware/software phase the developed software was programmed into the microcomputer units, and the integrated system was thoroughly tested. The tests revealed some minor problems, which were gradually removed. All channel safety, operational and test functions, regimes of operation, setting and calibration were checked.

After the integration hardware/software, thorough validation tests were accomplished. The first validation tests were accomplished with simulated input signals (a VXI based testing system programmed in HP VEE graphical development system instead of neutron chambers. After the successful control system tests, the IPP channel was tested in normal reactor operation.

3.3 Verification & Validation

The whole life cycle was accompanied by verification & validation. The software requirements were checked by reactor specialists to ensure that all features are correctly, completely and unambiguously implemented.

Next, the software design was compared with the software requirements to ensure that all requirements were correctly built into the design. The coding phase was verified by the checking of the coded software against the design. Also, software tests in the bottom-top manner were carried out.

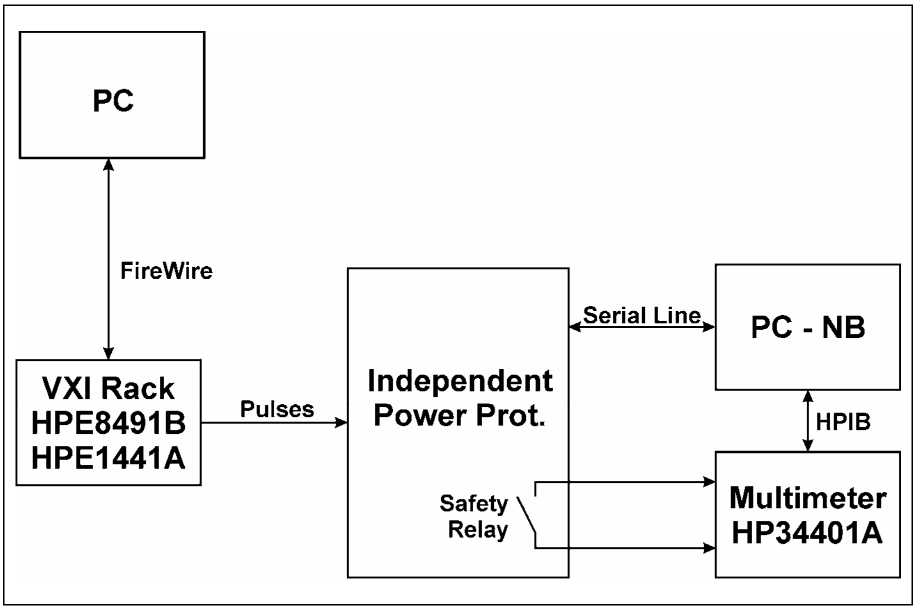

Figure 4: Block diagram of IPP validation tests

After the hardware/software integration, thorough validation tests were accomplished. The first validation tests were accomplished with simulated input signals instead of neutron chambers. The block diagram of the IPP validation test is shown in Figure 4. The arbitrary signal generator HPE1441A in a VXI rack provides a pulse signal. The PC controls the VXI devices via a FireWire line. The pulse signal is modified by a simple electronic circuit to get small pulses comparable with the neutron chamber signal. The output data from the IPP channel was received in the other PC (notebook). The signal of the IPP safety relay is scanned by the multimeter HP34401A. The notebook reads the safety relay status from the multimeter via the HPIB. The software for both computers was designed with the HP VEE graphical development tool. The IPP tests of power measurement, velocity of power changes measurement, power and velocity reactor scrams were carried out for both standard and stricter conditions.

After the successful simulated tests of the control system, the IPP channel was tested during normal reactor operation. The safety functions of the channel were first tested with standard and then stricter safety limits.

4 CONCLUSION

The contribution describes the control and independent power protection system upgrade of the VR-1 training reactor I&C. This upgrade substantially improves the reactor safety, the comfort of the reactor operation, and facilitates the maintenance. The I&C upgrade started in 2001 with the human-machine interface, continued in 2002 with the control rod motors, drives and safety circuits upgrade. The described control system and independent power protection upgrades were carried out in 2003 and 2005 respectively. The last stage will be the upgrade of the operational power measuring system in 2006 or 2007. The upgrades which have been and will be carried out will bring the reactor I&C to the top conditions and will enable a prolongation of their functionality and maintainability for at least next 10 years.

Reliable and safe operation is important because the training reactor VR-1 is very intensively used for training of students and future NPP staff. Every year, some 200 university students from The Czech Technical University in Prague, Charles University in Prague, Technical University in Brno and elsewhere get acquainted with the reactor. Worth mentioning is the co-operation with European universities like Fachhochschule in Aachen, The Technical University in Budapest, The Technical University in Vienna, The Slovak Technical University in Bratislava, and The Technical University in Delft. The reactor is also involved in some international programs such as the IAEA technical cooperation program and in the European programs ENEN and NEPTUNO for nuclear education [8].

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